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Formation and Propagation of Love Waves in a Surface Layer with a P-Wave Source

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The objective of this research is to investigate experimentally, and support with theoretical calculations, the formation and propagation of Love waves from a P-wave source due to scattering at material heterogeneities. The P-wave source is a spherical piezoelectric crystal cast in a surface layer of rock simulant over-laying a higher impedance granite substrate. Excitation of the piezoelectric crystal with a known voltage applies a spherical compressional pulse of known amplitude to the surrounding medium. Lateral heterogeneities cast in the surface layer convert incident P-wave energy into shear waves. The horizontally polarized shear waves (SH waves) trapped in the surface layer wave guide are the Love waves we will measure at the surface.
This report summarizes an investigation of the source by deriving an approximate analytic solution of a spherical crystal in an elastic medium. The analytic solution shows good agreement with experimental results of pressure histories measured in water at three locations from the source, and is then extended to an elastic medium. The elastic medium calculation is used to predict expected signal levels in a sensor evaluation experiment and determine the boundary (OVER)

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pressure history applied to the medium. The boundary pressure history will be used as input to finite element code calculations of the surface wave experiment to assist in the instrumentation design and analysis of the experimental results.

CONTENTS

FIGURES

OBJECTIVE AND APPROACH

Detection of underground nuclear explosions includes the spectral analysis of seismograms, an important portion of which is the contribution of Love waves. Field evidence suggests that it may be possible to discriminate between nuclear events and earthquakes by examining the Love wave records. The spectra for these events are different because an earthquake generates shear waves directly, whereas an underground explosion generates P-waves, from which Love waves are produced by scattering from material heterogeneities.

The objective of this research is to investigate experimentally, and support by theoretical calculations, the formation and propagation of Love waves from a P-wave source due to scattering at material heterogeneities. The approach is shown schematically in Figure 1. In these experiments, a spherical piezoelectric crystal (P-wave generator) is cast in a surface layer of rock simulant overlying a higher impedance granite substrate. Exitation of the piezoelectric crystal with a known voltage applies a pressure pulse of known amplitude to the cavity boundary, propagating compressional waves into the surrounding medium. Lateral heterogeneities of simple geometries (cylindrical and planar scattering surfaces) are cast into the surface layer, converting incident P-wave energy into shear waves. The horizontally polarized shear waves (SH-waves) trapped in the surface layer wave-guide are the Love Waves we will measure at the free-surface. The sensors at the surface will be distributed so both the undisturbed signal and the signals modified by scattering can be monitored at the surface.

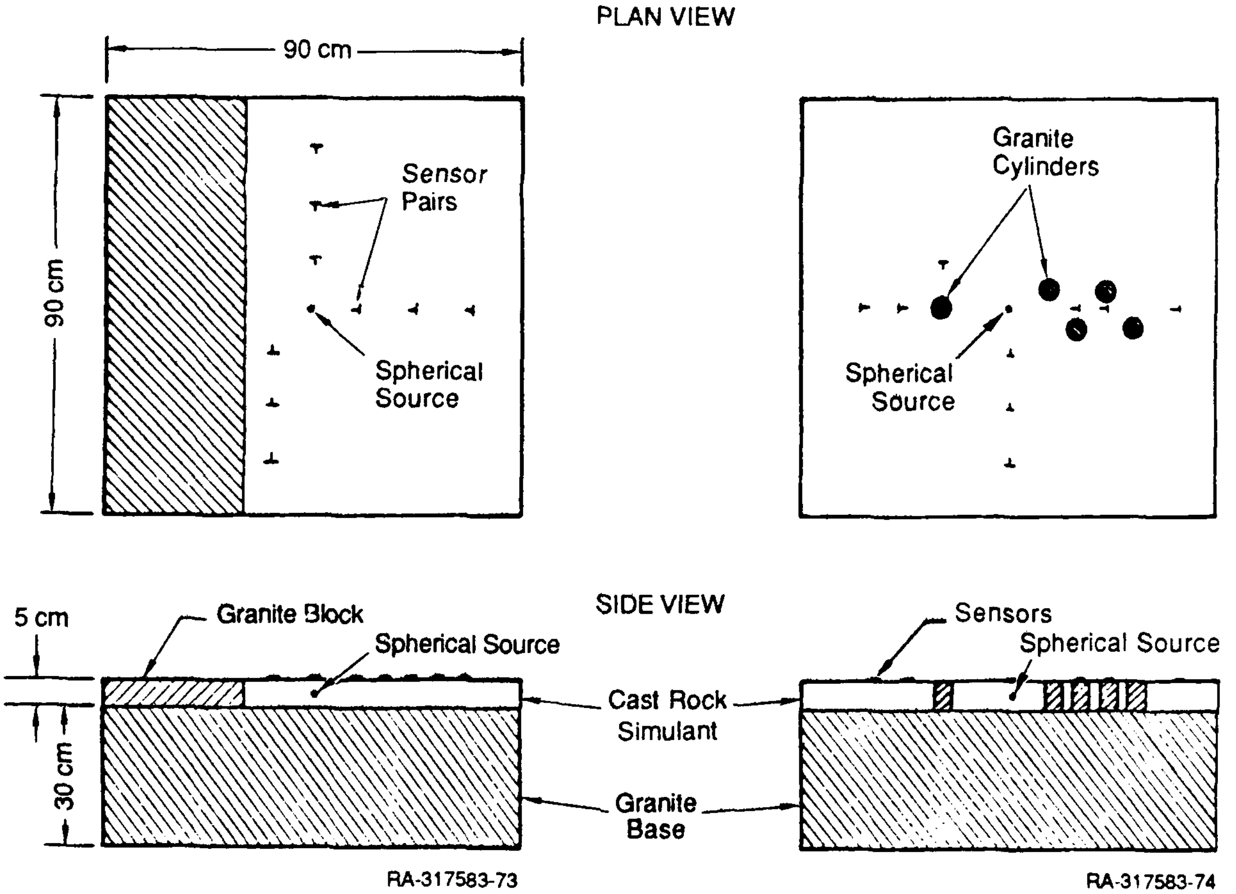


Figure (a) Model with planar scattering surface.

Figure (b) Model with single cylinder or array of cylinders as scattering objects.

Figure 1. Schematic of scale-model laboratory experiment.

PROGRESS

An analytic solution of a spherical piezoelectric crystal was derived to predict expected signal levels for a sensor evaluation experiment, and to provide a boundary pressure history as input for finite element code calculation.

SOLUTION OF A SPHERICAL PIEZOELECTRIC SOURCE IN AN ELASTIC MEDIUM

The source is a spherical shell of lead zirconate titanate ceramic, designated PZT-4, of outside radius $a = 0.6350$ cm, inside radius $b = 0.4826$ cm, and thickness $h = 0.1524$ cm. The electrical polarization is radial and the electrical and mechanical properties are spherically symmetric and transversely isotropic. In the usual spherical coordinate system (r,θ,ϕ), the properties are isotropic with respect to the circumferential coordinates (θ,ϕ).

The source is cast in a rock simulant, designated Pourstone, which is homogeneous and isotropic. Our analysis treats the source subjected to a voltage pulse and an interface reaction from the surrounding medium. This reaction is determined by an analysis of the spherical wave propagation in the surrounding medium caused by the reaction while ensuring equal radial displacements at the interface. Approximations are introduced to simplify the analysis without changing the basic dynamic response.

PIEZOELECTRIC SPHERICAL SHELL

The standard notations[1] for the physical quantities involved are

S_i	strain	
T_i	stress	N/m^2
E_m	electric field	V/m (N/C)
s_{ij}^E	elastic compliance coefficients	m^2/N
c_{ij}^E	elastic stiffness coefficients	N/m^2
d_{mi}	piezoelectric constants	m/V (C/N)
e_{mj}	piezoelectric constants	m/V (C/N)

The general relationships among the strain, stress, and electric field are

$$S_i = s_{ij}^E T_j + d_{mi} E_m \tag{1}$$

or

$$T_j = c_{ij}^E S_i - e_{mj} E_m \tag{2}$$

with

$$i,j = 1,2,\ldots,6 \qquad m = 1,2,3$$

Considerable simplification of equations (1) and (2) results when we make use of the general properties, $s_{ij} = s_{ji}$ and $c_{ij} = c_{ji}$, transverse isotropy (rotational symmetry about the x_3 axis), and spherically symmetric electrical excitation with $E_1 = E_2 = 0$. Then, equations (1) and (2) become

$$S_2 = S_1 = (s_{11} + s_{12})T_1 + s_{13}T_3 + d_{31}E_3 \tag{3a}$$

$$S_3 = 2s_{13}T_1 + s_{33}T_3 + d_{33}E_3 \tag{3b}$$

$$T_2 = T_1 = (c_{11} + c_{12})S_1 + c_{13}S_3 - e_{31}E_3 \tag{4a}$$

$$T_3 = 2c_{13}S_1 + c_{33}S_3 - e_{33}E_3 \tag{4b}$$

The local (x_1, x_2, x_3) triad is the spherical coordinate system (θ,ϕ,r). Thus, stress components T_1 and T_3 are T_θ and T_r, strain components S_1 and S_3 are S_θ and S_r, and the electric field component E_3 is E_r.

The equation of motion of a shell element is

$$\frac{\partial T_3}{\partial r} + \frac{2}{r}(T_3 - T_1) = \rho \frac{\partial^2 \xi}{\partial t^2} \tag{5}$$

in which $\xi(r,t)$ is the outward radial displacement and ρ is the density of the PZT-4. The strains are

$$S_1 = \frac{\xi}{r} \qquad S_3 = \frac{\partial \xi}{\partial r} \tag{6}$$

Substitution in (5) of the stresses from (4) followed by substitution of the strains from (6) leads to the governing equation

$$c_{33}\frac{\partial^2\xi}{\partial r^2} + 2c_{33}\frac{1}{r}\frac{\partial\xi}{\partial r} - 2(c_{11} + c_{12} - c_{13})\frac{\xi}{r^2} - \rho\frac{\partial^2\xi}{\partial t^2} = e_{33}\frac{\partial E}{\partial r} + 2(e_{33} - e_{31})\frac{E}{r} \tag{7}$$

where we have replaced the symbol E_3 by E. If the potential at the inner radius r = b is higher than the potential at the outer radius r = a by the voltage V, the field is

$$E(r,t) = \frac{ab}{a - b} \cdot \frac{V(t)}{r^2} \tag{8}$$

Then equation (7) becomes

$$c_{33}\frac{\partial^2\xi}{\partial r^2} + 2c_{33}\frac{1}{r}\frac{\partial\xi}{\partial r} - 2(c_{11} + c_{12} - c_{13})\frac{\xi}{r^2} - \rho\frac{\partial^2\xi}{\partial t^2} = -\frac{2ab}{a - b}\, e_{31}V(t)\frac{1}{r^3} \tag{9}$$

At the free inner boundary, r = b, the radial stress component is $T_3 = 0$ so by equations (4b), (6), and (8) this condition is

$$\frac{\partial\xi}{\partial r} + 2\frac{\xi}{r} = \frac{e_{33}}{c_{33}}\frac{ab}{a - b} \cdot \frac{V}{r^2} \qquad \text{at } r = b \tag{10}$$

The condition at the outer boundary depends on the problem being solved. For a traction free outer boundary, the condition is $T_3 = 0$ at r = a, that is,

$$\frac{\partial\xi}{\partial r} + 2\frac{\xi}{r} = \frac{e_{33}}{c_{33}}\frac{ab}{a - b} \cdot \frac{V}{r^2} \qquad \text{at } r = a \tag{11}$$

To obtain an upper bound on the interface pressure at r = a, we have $S_1 = S_2 = 0$ at r = a, that is,

$$\frac{\xi}{r} = 0 \qquad \text{at} \quad r = a \tag{12}$$

This condition corresponds to a spherical source in a rigid material. For our case of an elastic material, the condition at r = a is $T_3 = -p(t)$, the interaction pressure. The solution is a relationship between the radial displacement at r = a and the interaction pressure. By analyzing the problem of a pressure p(t) acting in a spherical cavity of radius r = a in an

elastic medium, we obtain a second relationship between cavity wall radial displacement and the pressure p(t). Equating the displacements gives an equation for the required interface pressure.

The governing equation (9) and the various boundary conditions can be solved explicitly but the results are extremely cumbersome. Therefore, for aiding the interpretation of experimental results, the source analysis is simplified by using thin shell theory. In this theory, the radial component of stress, T_3, is neglected.

Let the mean radius of the shell be $r = a$ and introduce the interface pressure $p(t)$ to be determined. The shell outward radial displacement is $\xi(t)$ and the thickness is h. The equation of motion is

$$\rho\ddot{\xi} = -\frac{2}{a}T_1 - \frac{p(t)}{h} \tag{13}$$

and if in equation (3a) we set $T_3 = 0$ and $S_1 = \xi/a$ to provide the average circumferential stress T_1 in equation (13), we obtain

$$\ddot{\xi} + \omega^2\xi = -\frac{p(t)}{\rho h} + \omega^2 a d_{31} E \tag{14}$$

where

$$\omega^2 = 2/\rho a^2(s_{11} + s_{12}) \tag{15}$$

The initial conditions of interest are

$$\xi(0) = 0 \qquad \dot{\xi}(0) = 0 \tag{16}$$

The solution of equation (14) satisfying the initial conditions (16) is

$$\xi(t) = \frac{1}{\omega}\int_0^t \left\{\omega^2 a d_{31} E(\tau) - \frac{1}{\rho h}p(\tau)\right\} \sin\omega(t - \tau)d\tau \tag{17}$$

If the driving electric field is

$$E(t) = E_o(1 - e^{-\alpha t}) \tag{18}$$

the shell velocity, according to the displacement (17), is given by

$$\frac{\dot{\xi}(t)}{v} = \frac{\alpha/\omega}{1 + (\alpha/\omega)^2}\left(\frac{\alpha}{\omega}\sin\omega t - \cos\omega t + e^{-\alpha t}\right) - \frac{1}{\rho h}\int_0^t p(\tau)\cos\omega(t-\tau)d\tau \tag{19}$$

where

$$v = \omega a d_{31} E_o \tag{20}$$

The velocity, v, is the maximum velocity achieved by the shell in a vacuum when subjected to a step voltage, E_o. Formula (19) gives the relationship between the shell radial velocity and the interaction pressure from the surrounding elastic medium.

SPHERICAL CAVITY IN AN ELASTIC MEDIUM[2]

When the stress-strain relationships

$$\sigma_r = (\lambda + 2\mu)\frac{\partial \xi}{\partial r} + 2\lambda\frac{\xi}{r} \tag{21}$$

$$\sigma_\theta = \lambda\frac{\partial \xi}{\partial r} + 2(\lambda + \mu)\frac{\xi}{r} \tag{22}$$

are substituted in the equation of motion

$$\frac{\partial \sigma_r}{\partial r} + \frac{2}{r}(\sigma_r - \sigma_\theta) = \rho_m\frac{\partial^2 \xi}{\partial t^2} \tag{23}$$

we obtain the displacement equation

$$\frac{\partial^2 \xi}{\partial r^2} + \frac{2}{r}\frac{\partial \xi}{\partial r} - \frac{2\xi}{r} = \frac{1}{c^2}\frac{\partial^2 \xi}{\partial t^2} \tag{24}$$

In (21) and (22), the σ_r and σ_θ are the radial and circumferential stress components, and λ and μ are the Lame constants for the isotropic elastic medium. In (23), ρ_m is the medium density. In (24), $c^2 = (\lambda + 2\mu)/\rho_m$ where c is the elastic wave velocity.

Introduction of the displacement potential φ defined by

$$\xi = \frac{\partial \varphi}{\partial r} \tag{25}$$

reduces (24) to

$$\frac{\partial^2 (r\varphi)}{\partial r^2} = \frac{1}{c^2} \frac{\partial^2 (r\varphi)}{\partial t^2} \tag{26}$$

The solution of (26) describing outgoing waves is

$$\varphi(r,t) = \frac{1}{r} f(s) \qquad s = t - (r - a)/c \tag{27}$$

In terms of the function f(s), the displacement, velocity, and stresses are

$$\xi = -\frac{f'}{cr} - \frac{f}{r^2} \tag{28}$$

$$\frac{\partial \xi}{\partial t} = -\frac{f''}{cr} - \frac{f'}{r^2} \tag{29}$$

$$\sigma_r = \rho c^2 \left\{ \frac{f''}{c^2 r} + \frac{2(1 - 2\vartheta)}{1 - \vartheta} \left(\frac{f'}{cr^2} + \frac{f}{r^3} \right) \right\} \tag{30}$$

$$\sigma_\theta = \frac{\rho c^2}{1 - \vartheta} \left\{ \frac{\vartheta f''}{c^2 r} - (1 - 2\vartheta) \left(\frac{f'}{cr^2} + \frac{f}{r^3} \right) \right\} \tag{31}$$

in which ϑ is Poisson's ratio.

For a given cavity wall velocity, $\dot{\xi}(t)$, we have, from (29), the equation

$$f''(s) + \frac{c}{a} f'(s) = ca\dot{\xi}(s) \tag{32}$$

and $f(0) = f'(0) = 0$ at the wave front $s = 0$. The solution is

$$f(s) = -\, cae^{-cs/a} \int_0^s e^{c\tau/a}\, \xi(\tau) d\tau \tag{33}$$

with

$$f'(s) = -\frac{c}{a} f(s) - ca\xi(s) \tag{34}$$

$$f''(s) = \frac{c^2}{a^2} f(s) - ca\xi'(s) + c^2\xi(s) \tag{35}$$

The cavity pressure required to maintain the cavity wall velocity is found by substituting (33), (34), and (35) in the radial stress formula (30) and setting $r = a$ $(s = t)$ and $\sigma_r(a,t) = -p(t)$. These steps give

$$p(t) = \rho c\dot{\xi}(t) - \frac{\rho c^2}{a}\left\{\frac{f(t)}{a^2} + \xi - \frac{2(1 - 2\vartheta)}{1 - \vartheta}\,\xi\right\} \tag{36}$$

with $f(t)$ given by (33) with $s = t$.

Formally, the velocity of the interface between the source and the medium is obtained by solving the equation that results from substituting the interface pressure (36) in the shell velocity equation (19). This equation is inconvenient so we introduce an approximation for the interface pressure (36). By integrating $f(t)$ from (33) by parts, we obtain

$$\frac{f(t)}{a^2} = -\,\xi + e^{(c/a)\tau} \int_0^t e^{(c/a)\tau}\, \dot{\xi}(\tau) d\tau \tag{37}$$

For an electric field excitation (18) on the sphere in a vacuum, the second term on the right hand side of (37) is much smaller than the first term if $\alpha << \omega$, which it is in our case. Assuming a similar relative magnitude when the source is embedded in a solid allows us to approximate $f(t)$ by

$$\frac{f(t)}{a^2} = -\,\xi$$

so that (36) simplifies to

$$p(t) = \rho c\dot{\xi}(t) + \frac{\rho c^2}{a}\frac{2(1 - 2\vartheta)}{1 - \vartheta} \cdot \xi(t) \tag{38}$$

Substitution of (38) in the shell equation (14) gives

$$\ddot{\xi} + 2\gamma\dot{\xi} + \Omega^2\xi = \omega v(1 - e^{-\alpha t}) \tag{39}$$

where

$$\gamma = \rho_m c/2\rho h \tag{40}$$

$$\Omega^2 = \omega^2 + (\rho_m c^2/\rho h a)[2(1 - 2\vartheta)/1 - \vartheta)] \tag{41}$$

and ρ_m is the density of the medium. The wave speed in the medium is defined by $c^2 = (\lambda + 2\mu)/\rho_m$. In terms of the stiffness coefficients, the angular frequency of the piezoelectric shell in a vacuum is given by

$$\omega^2 = 2(c_{11} + c_{12} - 2c_{13}^2/c_{33})/\rho a^2 \tag{42}$$

In (39), the velocity, v, is given by (20).

The solution of equation (39) satisfying the initial conditions (16) is

$$\frac{\Omega^2}{\omega v}\xi(t) = 1 - \frac{1}{\bar{\Omega}^2 + (\gamma - \alpha)^2}$$

$$\left\{\Omega^2 e^{-\alpha t} - a e^{-\gamma t}\left[(2\gamma-\alpha)\cos\bar{\Omega}t - \frac{\Omega^2 - \gamma(2\gamma-\alpha)}{\bar{\Omega}}\sin\bar{\Omega}t\right]\right\} \tag{43}$$

where

$$\bar{\Omega}^2 = \Omega^2 - \gamma^2 \tag{44}$$

For excitations with rise times that are long compared to the natural quarter period, we have $\alpha^2 << \bar{\Omega}^2$ and the radial displacement (43) becomes

$$\frac{\Omega^2}{\omega v} \cdot \xi(t) = 1 - e^{-\alpha t} - \frac{\alpha}{\overline{\Omega}} e^{-\gamma t} \sin\overline{\Omega} t \tag{45}$$

The shell radial velocity obtained by differentiating (45) is,

$$\frac{\Omega^2}{\alpha\omega v} \dot{\xi}(t) = e^{-\alpha t} - e^{-\gamma t}\left(\cos\overline{\Omega} t - \frac{\gamma}{\overline{\Omega}} \sin\overline{\Omega} t\right) \tag{46}$$

Substitution of $\xi(\tau)$ from (45) into (33) and performing the integration gives

$$-\frac{\Omega^2}{a^2\omega v} f(s) = 1 - \frac{1}{(c/a) - \alpha}\left(\frac{c}{a} e^{-\alpha s} - \alpha e^{-(c/a)s}\right) - \frac{\alpha(c/a)}{\Omega^2} \bullet$$

$$\left\{e^{-(c/a)s} - e^{-\gamma s}\left(\cos\overline{\Omega} s - \frac{(c/a) - \gamma}{\overline{\Omega}} \sin\overline{\Omega} s\right)\right\} \tag{47}$$

Formulas (34) and (35) determine f'(s) and f"(s) because $\xi(s)$, $\xi'(s)$, and f(s) are given by (45), (46), and (47). Consequently, we can determine ξ, $\dot{\xi}$, σ_r, and σ_θ by (28)-(31).

FLUID MEDIUM

If we set $\vartheta = 1/2$ in the frequency formula (41),

$$\Omega^2 = \omega^2 \tag{48}$$

and, by (44)

$$\overline{\Omega}^2 = \omega^2 - \gamma^2 \tag{49}$$

where the fluid wave velocity is $c = (K/\rho_m)$, K being the fluid bulk modulus. In our case, $\gamma \ll \omega$ so (45), (46), and (47) become

$$\xi(s) = \frac{v}{\omega}\left(1 - e^{-\alpha s} - \frac{\alpha}{\omega} e^{-\gamma s} \sin\omega s\right) \tag{50}$$

$$\xi'(s) = \frac{v\alpha}{\omega}\left\{e^{-\alpha s} - e^{-\gamma s}\left(\cos\omega s - \frac{\gamma}{\omega} \sin\omega s\right)\right\} \tag{51}$$

$$-\frac{\omega}{a^2 v} f(s) = 1 - \frac{1}{(c/a) - \alpha}\left\{\frac{c}{a} e^{-\alpha s} - \alpha e^{-(c/a)s}\right\}$$

$$-\frac{\alpha(c/a)}{\omega^2}\left\{e^{-(c/a)s} - e^{-\gamma s}\left(\cos\omega s - \frac{(c/a) - \gamma}{\omega}\sin\omega s\right)\right\} \tag{52}$$

Stress formulas (30) and (31) are replaced by the pressure formula

$$p = -\rho_m f''(s)/r \tag{53}$$

where f''(s) is determined by (35), (50), (51), and (52).

NUMERICAL VALUES (SOLID MEDIUM)

The properties we require of the PZT-4 ceramic are

Elastic compliance coefficients (m^2/N)

S^E_{11}	12.30×10^{-12}
S^E_{12}	-4.05×10^{-12}
S^E_{13}	-5.31×10^{-12}
S^E_{33}	15.50×10^{-12}

Elastic stiffness coefficients (N/m^2)

c^E_{11}	13.90×10^{10}
c^E_{12}	7.78×10^{10}
c^E_{13}	7.43×10^{10}
c^E_{33}	11.50×10^{10}

Piezoelectric constants (m/V, c/N)

d_{31}	-123×10^{-12}
d_{33}	289×10^{-12}

Piezoelectric constants (Nm/V, c/m^2)

e_{31}	-5.20
e_{33}	15.10
Density ρ	7.5×10^3 kg/m^3

The properties of the 'Pourstone' medium are

Young's modulus	E	16.4 GPa
Shear modulus	μ	6.3 GPa

Bulk modulus	K	13.8 GPa
Poisson's ratio	ϑ	0.3
Lame constant	λ	9.6 GPa
Density	ρ_m	1.79×10^3 kg/m^3
P-wave velocity	c_p	3.52 mm/μs (km/s)
S-wave velocity	c_s	1.88 mm/μs (km/s)

The dimensions of the spherical source are

Outer radius	a	6.350 mm
Inner radius	b	4.826 mm
Thickness	h	1.524 mm

The driving voltage, V(t), is taken in the form

$$V(t) = V_o\left(1 - e^{-\alpha t}\right) \qquad (54)$$

applied to the outside of the spherical shell. If the value at the midradius, (a + b)/2, is chosen to represent the field strength, then according to (8) and (54),

$$E(t) = -\,644\ V_o\left(1 - e^{-\alpha t}\right) \qquad \text{volts/m}$$

By letting the voltage reach 90% of V_o in 20 μs, the value of α is determined as $\alpha = 0.115$ μs^{-1}. Also, if $V_o = 300$ volts, we have $E_o = -0.1932 \times 10^6$ volts/m. Hence,

$$E(t) = -\,0.1932 \times 10^6(1 - e^{-0.115\,t})$$

where t has μs units.

The natural angular frequency of the spherical source (in a vacuum), according to (15), is $\omega = 0.895 \times 10^6$ rad/s and the natural frequency is $f = \omega/2\pi = 142$ kHz.

If the voltage is applied slowly to the free shell, the maximum radial displacement is

$$\xi_s = a d_{31} E_o = 0.15 \times 10^{-3}\ \text{mm} = 0.15\ \mu\text{m}\ .$$

If the same voltage (300 volts) is applied instantaneous, the maximum displacement is $2\xi_s$, and the maximum velocity is

$$\max \dot{\xi} = v = \omega a d_{31} E_o = \omega \xi_s = 13.4\ \text{cm/s}\ .$$

If the voltage is applied slowly to the shell confined by a rigid medium, the interface pressure is $p = -(2h/a)T_1$ where the circumferential stress is $T_1 = -d_{31}E_o/(s_{11} + s_{12})$. The magnitude of this pressure is p = 14.05 bars (206 psi).

In Equation (39) governing the shell motion in an elastic medium, the numerical values of γ and Ω, and consequently $\overline{\Omega}$ are

$$\gamma = 0.276 \times 10^6 \text{ rad/s} \qquad \Omega = 1.073 \times 10^6 \text{ rad/s} \qquad \overline{\Omega} = 1.037 \times 10^6 \text{ rad/s}$$

For comparison, we note that $\alpha = 0.115 \times 10^6 \text{ s}^{-1}$. Because $\alpha^2 << \overline{\Omega}^2$ formulas (45), (46), and (47) for the shell radial displacement and velocity and the potential function f(s) are applicable. The value of c/a occurring in f(s) is $c/a = 0.554 \times 10^6 \text{ s}^{-1}$.

The oscillatory part of the solution has a frequency of $\bar{f} = \overline{\Omega}/2\pi = 165$ kHz with a period of $\overline{T} = 1/\bar{f} = 6\ \mu s$.

NUMERICAL VALUES (WATER)

Using a density of $\rho_m = 1$ gram/cm^3 and a bulk modulus of K = 2.245 GPa (22.45 kbar), we obtain

Wave velocity	$c = (K/\rho_m)^{1/2} = 1.50$ mm/μs
Damping parameter	$\gamma = 0.066 \times 10^6$ rad/s
Spring parameter	$\Omega = \omega = 0.895 \times 10^6$ rad/s
Angular frequency	$\overline{\Omega} = 0.893 \times 10^6 \text{ rad/s} \approx \Omega$
Velocity parameter	$c/a = 0.236 \times 10^6 \text{ s}^{-1}$
Excitation parameter	$\alpha = 0.115 \times 10^6 \text{ s}^{-1}$

APPLICATION OF SOLUTION IN A WATER MEDIUM

We applied the solution just derived for the case of a spherical piezoelectric source in a water medium, and compared the calculated and measured pressure histories at three radii from the source. The experimental configuration is shown in Figure 2. In the experiments, the crystal was excited with a known voltage history, and free-field water pressure histories were measured at radii of 0.91, 1.51, and 3.38-cm measured from the center of the source. The input voltage history to the crystal is shown in Figure 3. The voltage reaches 90 % of the peak value of 316 volts at 10 μs, so in the formulation

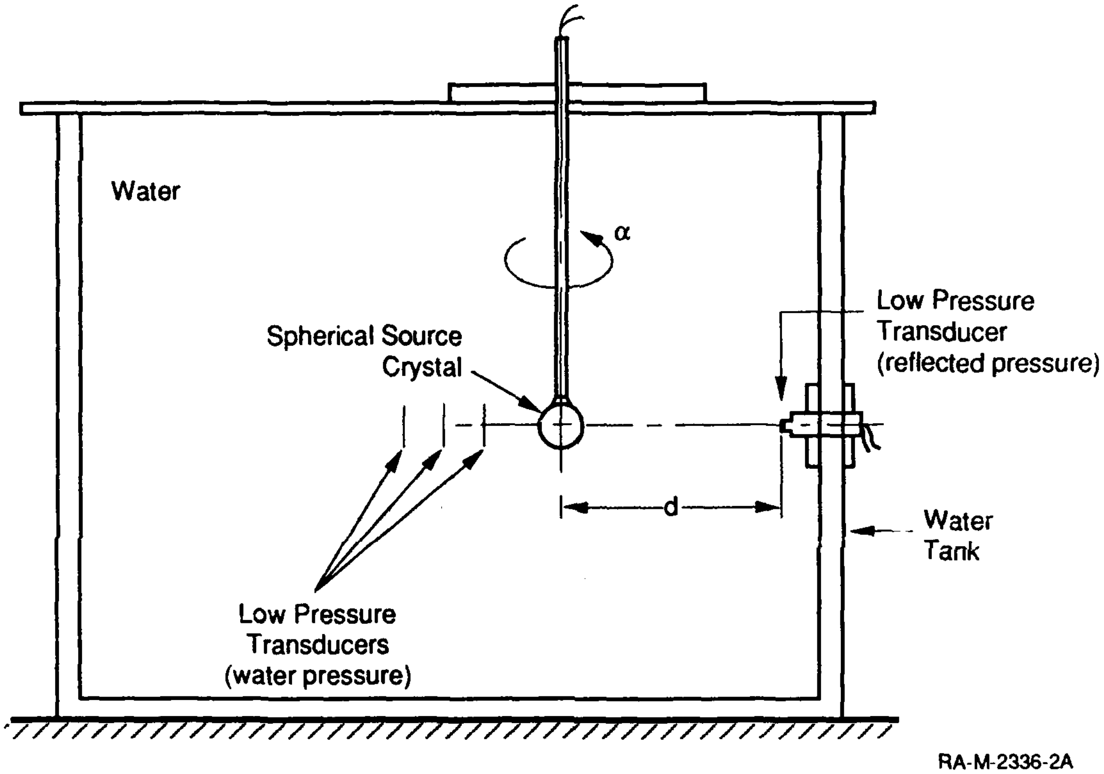


Figure 2. Configuration for measuring stress pulse amplitudes in water at different radii from the source and sphericity of piezoelectric source.

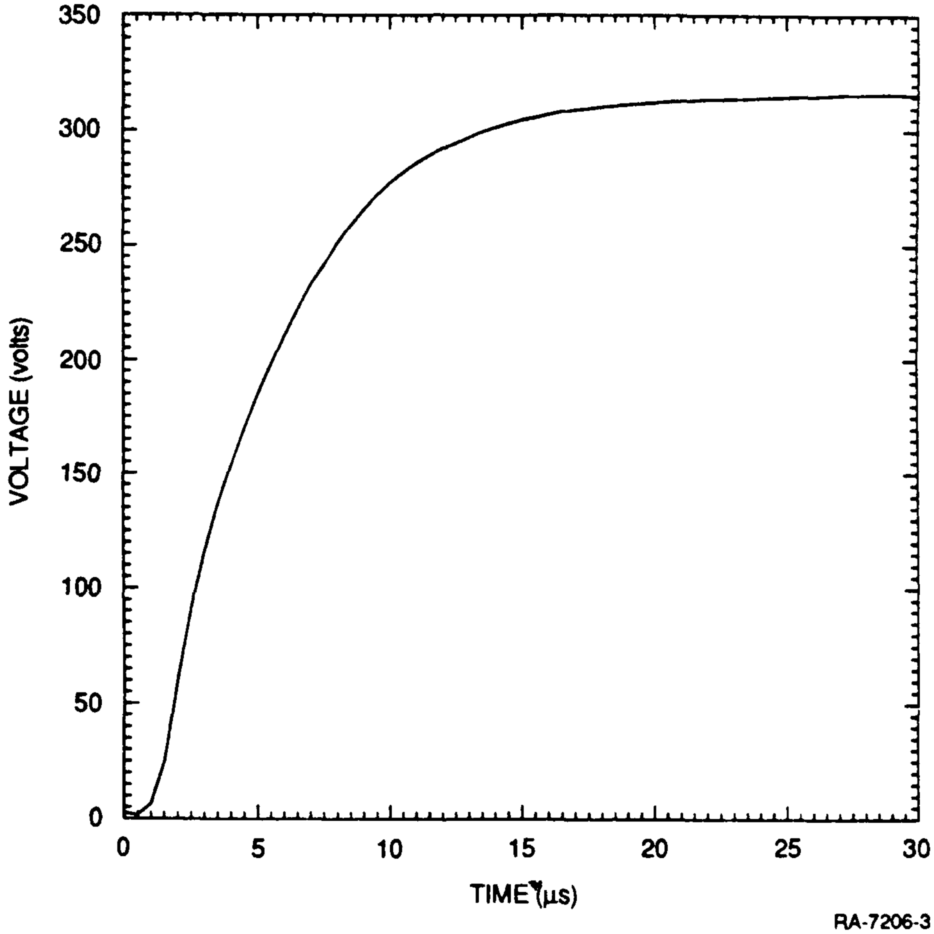


Figure 3. Input voltage history to the piezoelectric source in the water pressure experiment.

described previously, the value of α is $0.230 \times 10^6\ \mu s^{-1}$, and the field strength as a function of time is described by:

$$E(t) = -\ 0.2075 \times 10^6\ (1 - e^{-0.23\ t})$$

where the field strength, E(t), has units Volts/m and t has units μs.

The calculated and measured pressure histories are shown superposed for the three gage locations in Figure 4, 5, and 6. At the first gage location, the measured and calculated histories show very good agreement in oscillation frequency and peak amplitude. At the further out locations, the measurements show larger damping than predicted by the calculation, but satisfactory agreement is observed in peak pressure and the oscillation frequency.

APPLICATION OF SOLUTION TO AN ELASTIC MEDIUM

The agreement between calculation and experiment in a water medium is sufficient to extend the solution to an elastic medium and estimate the expected amplitudes of velocity and displacement at different ranges in the medium. In addition, the calculated pressure history at the source/medium interface can be used as an input boundary condition for finite element calculations of the experiment shown in Figure 1. The results of the finite element calculations will be useful for estimating expected signal levels on the surface and assist is instrumentation selection for that experiment. The elastic medium is a rock simulant called pourstone, with the elastic properties listed on page (16). Using the same voltage history shown in Figure 3 as the input, the calculated velocity histories at radii of 0.635 cm (source/medium interface), 1.5- and 2.5-cm are shown superposed in Figure 7. The corresponding displacements for the three locations are shown in Figure 8, and the radial and circumferential stress histories are shown in Figures 9 and 10, respectively.

EVALUATION EXPERIMENT IN POURSTONE

We performed experiments to compare the calculated and measured velocity and displacement histories in a sphere of pourstone. The experimental configuration is shown in Figure 11. In this experiment, copper loops were cast in the midplane of a 12-cm diameter sphere of pourstone to measure radial particle velocity histories at different radii from the source. The specimen is placed in an external magnetic field, and we measure the induced voltage as the conductor cuts flux lines during passage of the stress wave. The particle velocity is proportional to the induced voltage, the magnetic field strength, and the

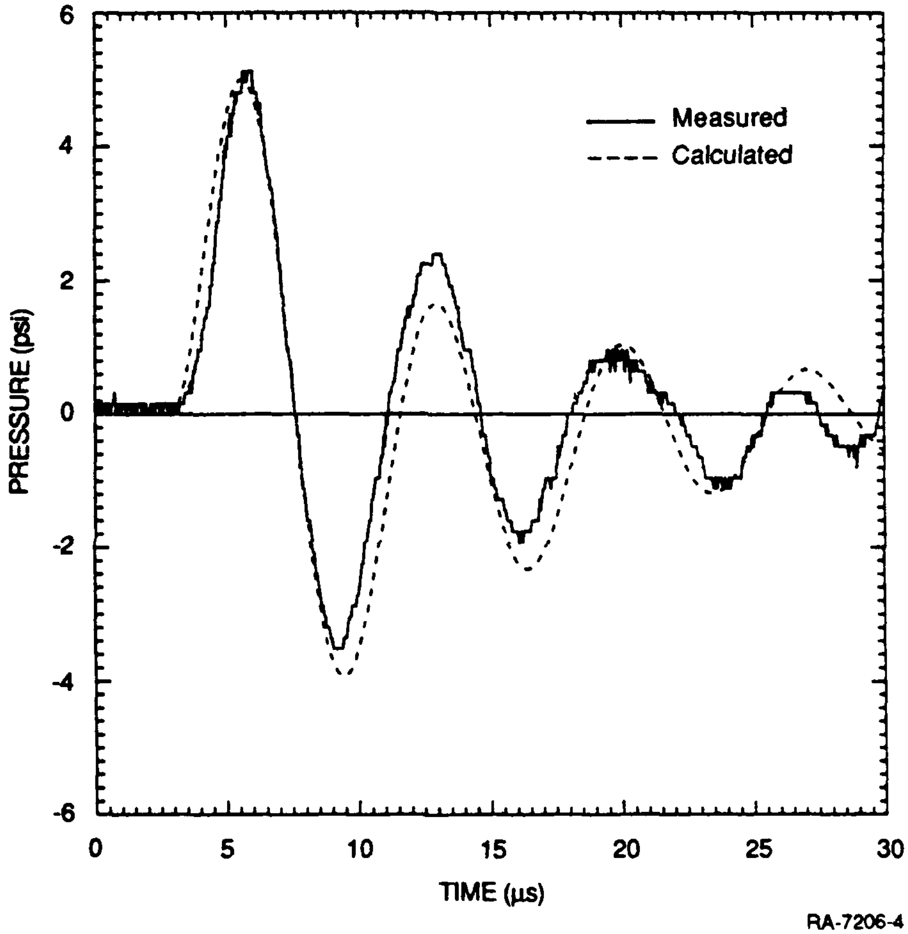


Figure 4. Comparison of measured and calculated pressure histories in water at a range of 0.91-cm from the center of the source.

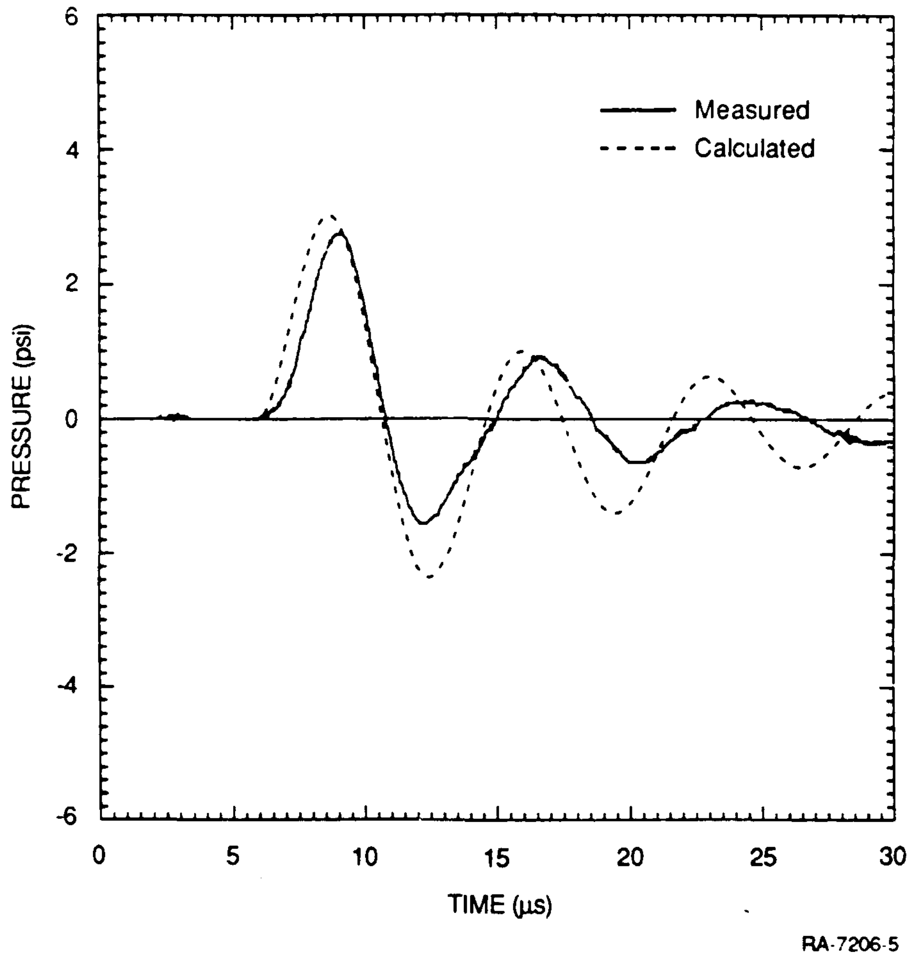


Figure 5. Comparison of measured and calculated pressure histories in water at a range of 1.51-cm from the center of the source.

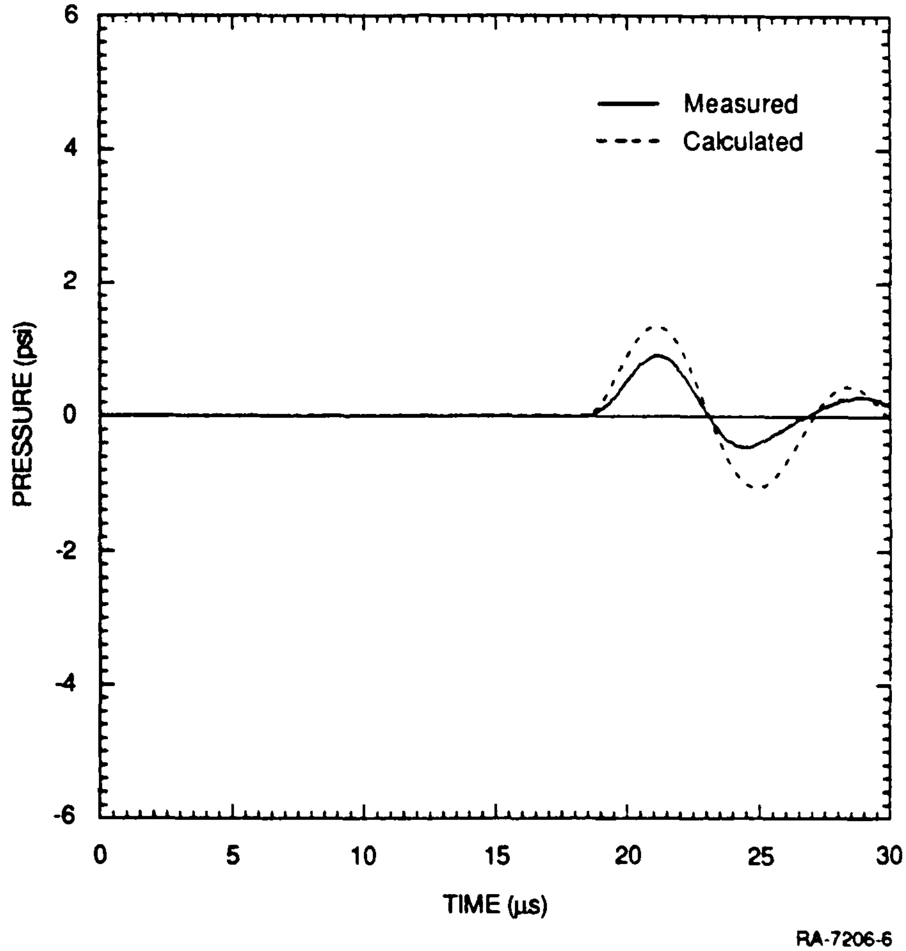


Figure 6. Comparison of measured and calculated pressure histories in water at a range of 3.38-cm from the center of the source.

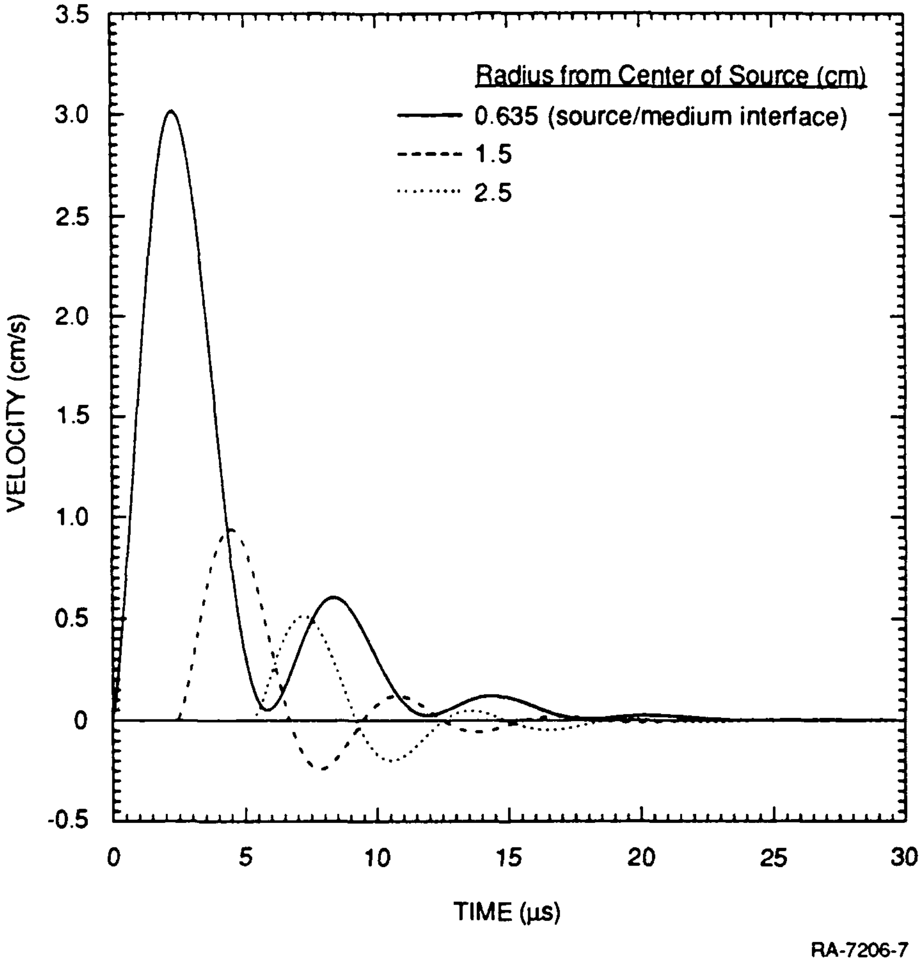


Figure 7. Calculated velocity histories at 3 ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts.

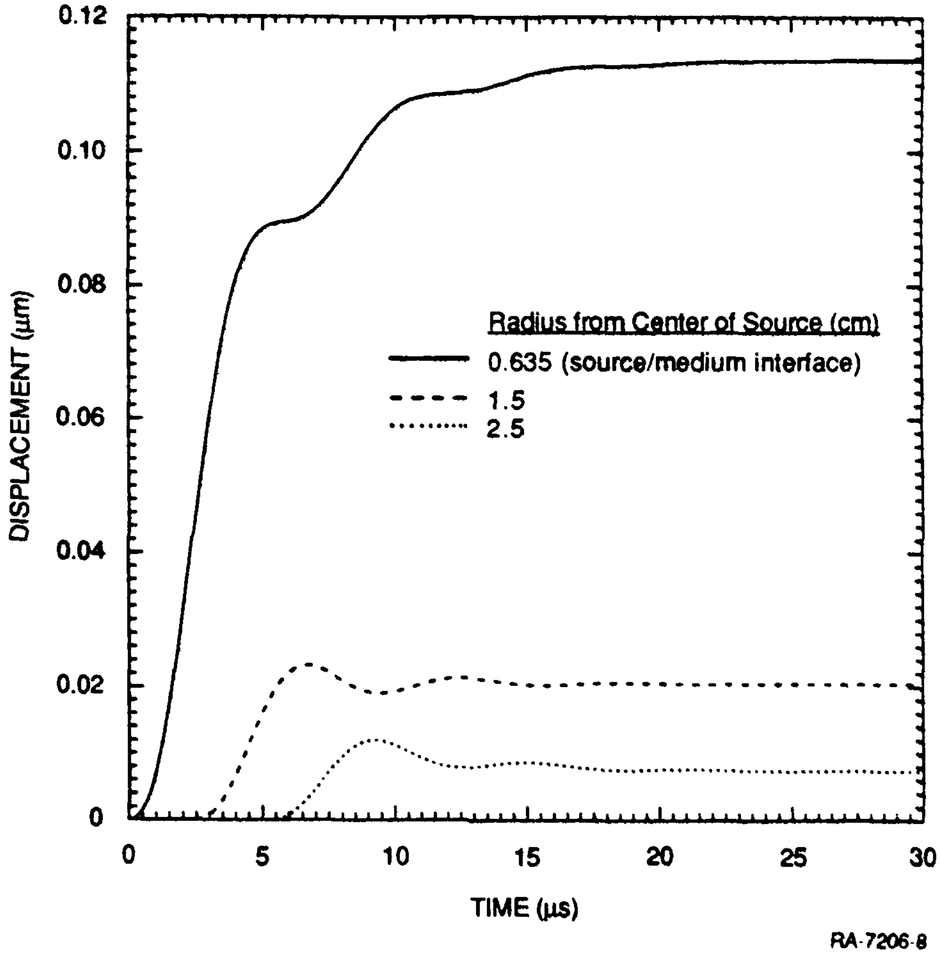


Figure 8. Calculated displacement histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts.

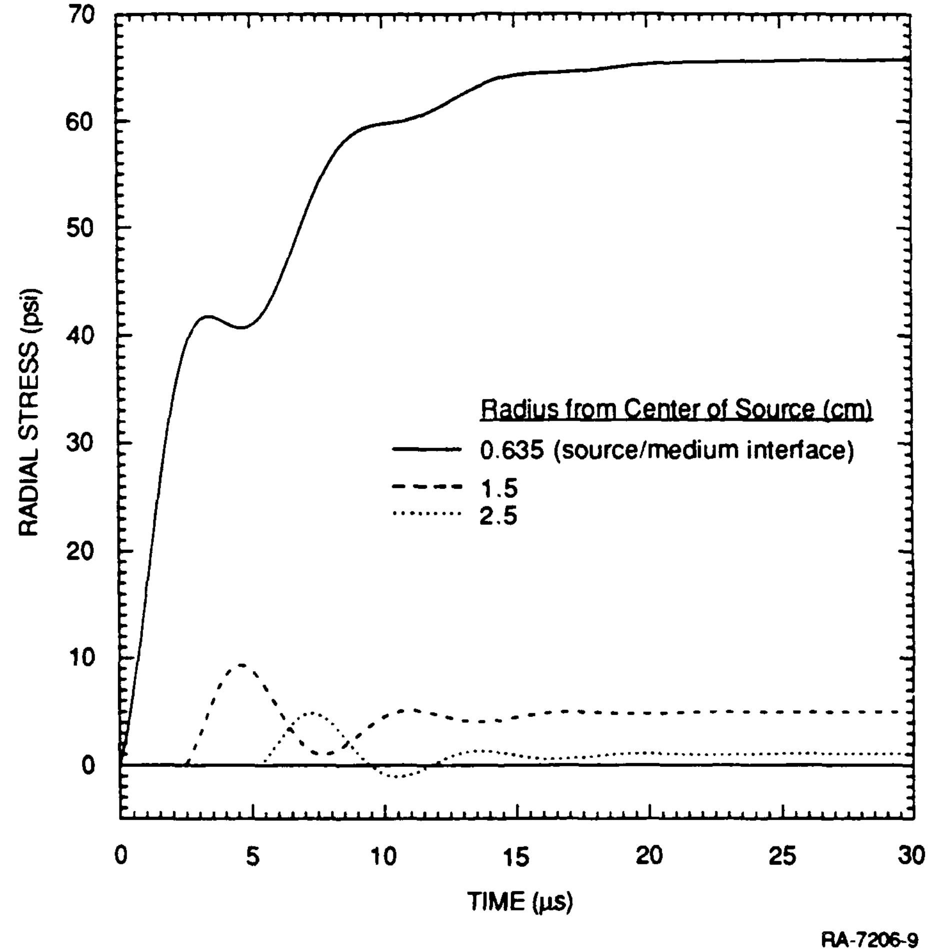


Figure 9. Calculated radial stress histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts.

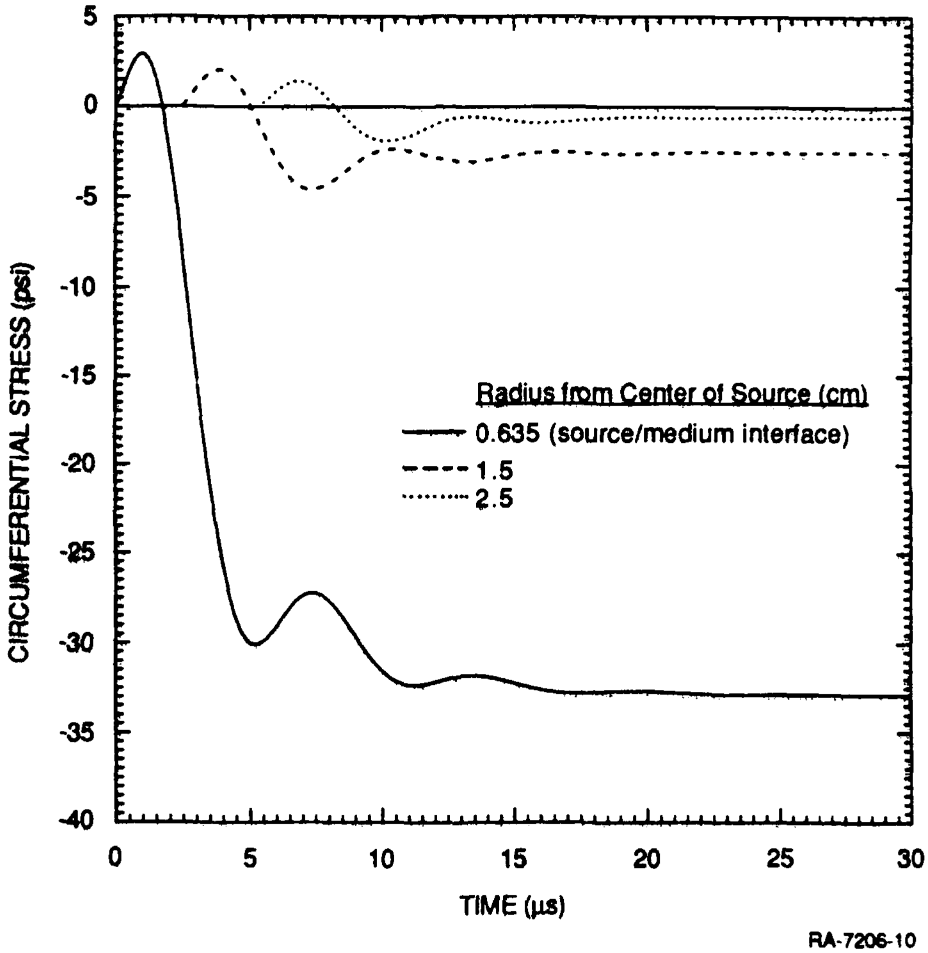
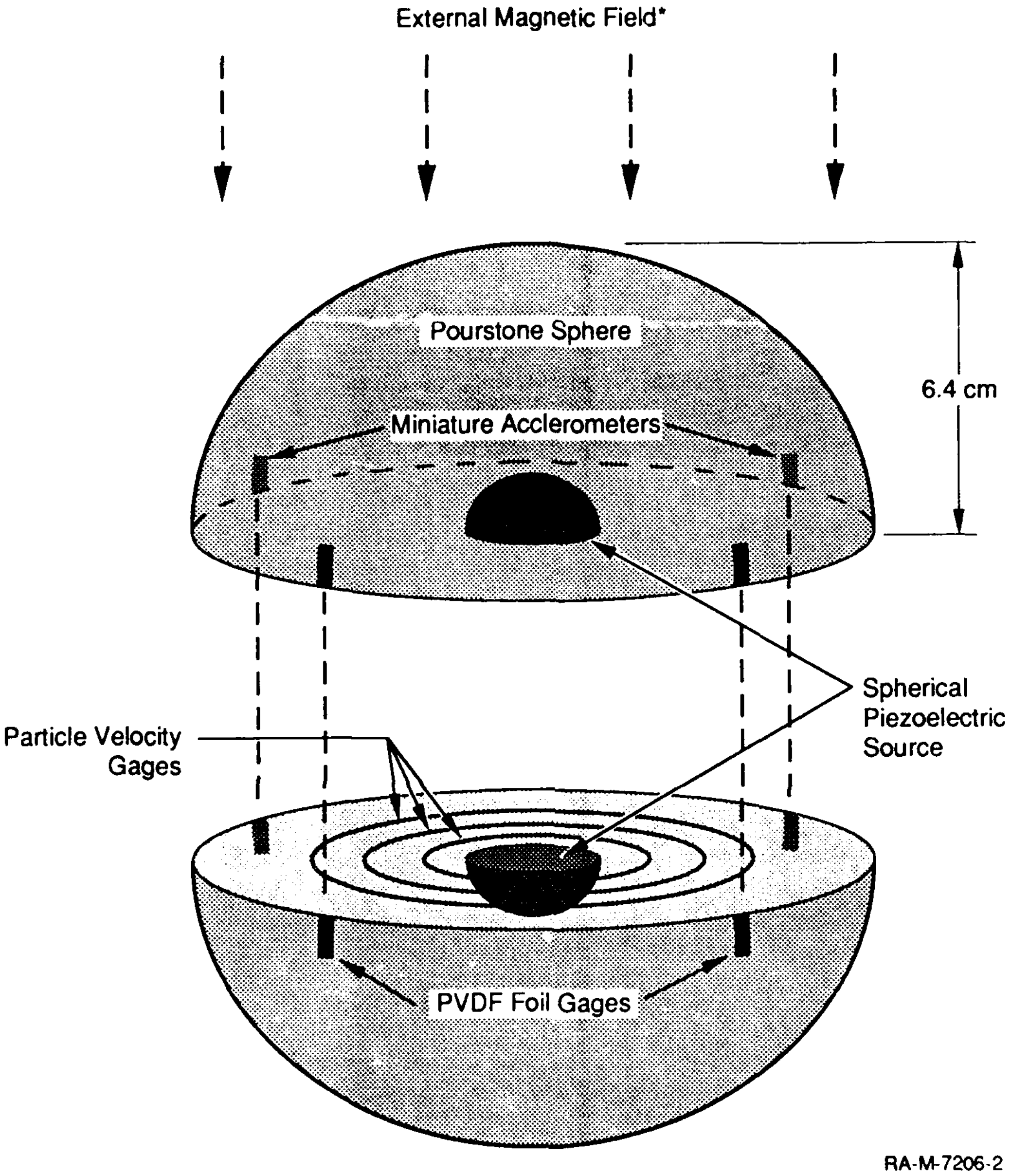


Figure 10. Calculated circumferential stress histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts.



* Particle Velocity Measurements Only

Figure 11. Configuration for source/sensor evaluation experiment.

length of the conductor. To increase the expected signal, we increased the gage length by constructing gages consisting of 10 windings of copper wire. Accelerometers and PVDF foils were mounted on the surface of the sphere to measure free-surface acceleration and strain, respectively.

We are currently analyzing the data obtained from the particle velocity gages. The accelerometers and PVDF foils did not produce satisfactory signals because the range of the measurement was too large. Consequently, we plan to fabricate a smaller specimen to evaluate these gages at locations closer to the source.

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